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ESTUDIOS

A multi-level approach to exploring the associations between reading, spelling, and math skills

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Abstract: In this study, we utilized network analysis to examine with standard clinical tests the predictions of the multi-level model of cognitive skill learning proposed by Zoccolotti et al. (2020b) on the relationships among different learning domains. To achieve this, we administered a series of reading, spelling, and math tasks to 98 children (mean age: 8.19 years) attending 2nd to 5th grade. The network analysis evidenced positive links within each area, consistent with the prediction that reading, spelling and math refer to three partially distinct domains calling for different core competences. Another expectation was that the associations among these learning domains would be mediated by tests that involve retrieving individual memories (instances). Supporting this prediction, the three tests measuring instance-based processing - Orthographic Judgment, Ambiguous Words, and Arithmetic Facts - were crucial in linking the three learning domains. Furthermore, the model posits that some associations among different learning areas may be influenced by the format or response characteristics, referred to as "performance" factors. We identified two such cases in the observed network: a strong link between reading speed and calculation speed, which is closely related to speed requirements, and a robust connection between reading accuracy and context-sensitive words, interpreted as a need for careful orthographic analysis. Overall, the results largely confirm the model's predictions, highlighting specific and common factors contributing to performance in reading, spelling, and math.
Keywords: Math; Learning disorders; Network analysis; Reading; Spelling.

ESP Una aproximación multinivel a la asociación entre la lectura, el deletreo y las habilidades matemáticas

Resumen: En este estudio utilizamos un análisis de redes para examinar con pruebas clínicas estándar las predicciones del modelo multinivel de aprendizaje de habilidades cognitivas propuesto por Zoccolotti et al. (2020b) sobre las relaciones entre los distintos dominios de aprendizaje. Para ello, administramos una serie de tareas de lectura, deletreo y matemáticas a 98 niños (edad media: 8,19 años) que cursaban entre 2° y 5° curso. El análisis de la red evidenció vínculos positivos dentro de cada área, en consonancia con la predicción de que la lectura, el deletreo y las matemáticas se refieren a tres dominios parcialmente distintos que exigen competencias básicas diferentes. Otra hipótesis era que las asociaciones entre estos dominios de aprendizaje estarían mediadas por pruebas que implican la recuperación de recuerdos individuales (instancias). En apoyo de esta predicción, las tres pruebas que miden el procesamiento basado en instancias (juicio ortográfico, palabras ambiguas y pruebas aritméticos) fueron cruciales para vincular los tres dominios de aprendizaje. Además, el modelo postula que algunas asociaciones entre diferentes áreas de aprendizaje pueden estar influidas por el formato o las características de la respuesta, denominados factores de "rendimiento". Identificamos dos casos de este tipo en la red observada: un fuerte vínculo entre la velocidad de lectura y la velocidad de cálculo, estrechamente relacionada con los requisitos de velocidad, y una sólida conexión entre la precisión lectora y las palabras sensibles al contexto, interpretada como la

necesidad de un análisis ortográfico cuidadoso. En conjunto, los resultados confirman ampliamente las predicciones, poniendo de relieve los factores específicos y comunes que contribuyen a la realización de las pruebas de lectira, deletreo y matemáticas.
Palabras clave: Análisis de redes; Deletreo; Lectura; Matemáticas; Trastornos del aprendizaje.

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Introduction

There is a long tradition of studying reading, spelling, and mathematics. These studies have focused on the development of these skills and examined children with atypical behaviors. Until the end of the last century, the emphasis in this research was quite narrow. Specifically, reading, spelling, and math skills were mostly investigated separately. This trend is evident in several ways. For instance, considerable effort has been devoted to developing cognitive models. Notably, distinct models have been proposed for reading (*e.g.*, Coltheart et al., 2011; Seidenberg & McClelland, 1989), spelling (*e.g.*, Houghton & Zorzi, 2003; Tainturier & Rapp, 2001), and mathematics (*e.g.*, Dehaene, 1992; McCloskey et al., 1985). Additionally, this trend is reflected in the perspectives adopted by international diagnostic manuals, such as the DSM and ICD, which referred to separate and distinct learning disorders, i.e., dyslexia, dysgraphia, and dyscalculia.

By the turn of the century, the focus of research had shifted significantly. Notably, there has been an increasing interest in the widespread comorbidities among learning disorders (Landerl & Moll, 2010; Moll et al., 2019), particularly in relation to other developmental disorders such as ADHD (Willcutt et al., 2005) and language impairment (Pennington & Bishop, 2009). In a comprehensive review of existing literature, Pennington (2006) emphasized the dangers of attributing developmental disorders to single, isolated causes. Instead, the prevalence of associations among various developmental disorders suggests a need to adopt a multifactorial approach. This perspective requires researchers to identify both the factors that contribute to the unique characteristics of disorders like dyslexia, ADHD, and language impairments (the focus of Pennington's analysis) and the factors that lead to their overlapping features. This authoritative theoretical framework has spurred research into the factors that may explain the overlap between dyslexia and dyscalculia (*e.g.*, Peters et al., 2020) as well as the association between dyslexia and ADHD (*e.g.*, Boada et al., 2012).

This change in perspective is also reflected in the way learning disorders are described in international manuals. For instance, the DSM-5 lists a single "*learning disorder*," although it includes various "*specifiers*" to classify the current manifestation at the time of assessment. According to Tannock (2013), a key factor in altering this perspective was the "*questionable discreteness and coverage of the DSM-IV categories of learning disorders*." In other words, the DSM acknowledges the partial overlap among these disorders and modifies its diagnostic categories accordingly.

An interesting perspective on evaluating learning disorders is proposed by the recent NIMH Research Domains Criteria (Cuthbert, 2014). This research program highlights the limitations of viewing developmental disorders as isolated entities and promotes research from a "*transdiagnostic*" perspective. For example, Astle et al. (2022) conduct a thorough analysis of the limitations of the case-control design commonly used in studies of dyslexia or dyscalculia. In these studies, children with dyslexia are compared to a control group matched by age or, sometimes, by reading level. However, little attention is given to the fact that children with dyslexia often have various comorbidities that can influence the results in unpredictable ways. Conversely, Astle et al. (2022) suggest using different methodologies to detect emerging trends in the data without preconceiving diagnostic labels. Techniques such as cluster analysis or network analysis can be employed. This "*transdiagnostic revolution in neurodevelopmental disorders*" expands the spectrum of potentially relevant methodologies (Astle et al., 2022). It encourages different methods of recruitment by diagnosis, including cross-syndrome comparison designs, diagnosis-blind studies, and studies involving co-occurring diagnoses, as well as recruitment based on functional definitions, such as community screenings, or unselective recruitment, such as regional or national cohorts (Astle et al., 2022). These latter studies focus on data-driven methodologies like hierarchical clustering or network analysis.

As stated above, cognitive models have primarily focused on specific learning domains, such as reading, spelling, or math, with minimal interaction between these areas. In our research, in keeping with the methodological changes envisaged by Astle et al. (2022), we aimed to identify the unique and common factors that influence performance in reading, spelling, and math among an unselected sample of fourth graders (Zoccolotti et al., 2020a). Our findings revealed that some tasks predicted performance in only one learning domain. For example, a task of visual-auditory pseudo-word matching (orthographic decoding) was a strong predictor of reading performance but did not correlate with written spelling to dictation or arithmetic skills. On the other hand, some tasks effectively predicted performance across different learning domains. For instance, an orthographic decision task was able to predict outcomes in both reading and spelling. We also observed that tasks predicting performance across different domains could be interchangeable. In a regression model, the performance on the orthographic decision task was similarly predictive of success in math tasks as it was the performance on an arithmetic facts task. Notably, the reverse was also true: performance on the arithmetic facts task also effectively predicted reading and spelling outcomes when it replaced the orthographic decision task. Importantly, tasks that demonstrated a cross-domain impact required reference to established individual memories (i.e., the retrieval of a single memory trace from memory, e.g., for orthographic representations or arithmetical facts), which we refer to as "instances", following the theoretical framework proposed by Logan (1988, 1992).

The performance on reading, spelling, and math tasks appears to depend on at least two components. One component involves identifying the underlying rules of the specific learning task–such as orthographic decoding in reading–while the other is related to the ability to retrieve individual memories to enhance performance effectively. In mathematics, children draw on prior knowledge to streamline and improve their performance on arithmetic tasks. Although it is possible to perform arithmetic operations using algorithmic methods alone, relying on basic arithmetic facts makes computations easier and quicker. Similar principles apply to reading and writing tasks. In regular orthographies, such as Italian–the focus of this study–accurate reading and spelling can be achieved solely by applying the grapheme-to-phoneme and phoneme-to-grapheme conversion rules, respectively. Nevertheless, leveraging lexical knowledge can make reading and spelling smoother and more effective. Based on these observations, we proposed that rule-based processing explains the specificity of different learning domains (Zoccolotti et al., 2020b). In contrast, the ability to consolidate and retrieve individual memories is a skill that spans across domains and accounts for the overlaps in learning performance, which may also play a role in the comorbidity of learning disorders (Zoccolotti et al., 2020b).

The multi-level model of cognitive skill learning proposed by Zoccolotti et al. (2020b), as shown in Figure 1, outlines the relationships between various learning behaviors, *i.e.*, reading, spelling, and math and may be instrumental in understanding these performances more unitarily as done in the present study. The model suggests that distinct competencies selectively influence learning in each area: orthographic-phonological binding for reading, phonological processing for spelling, and number module for math. A deficit in any of these competencies would primarily impact a single learning domain. However, performance across different domains is also influenced by a factor referred to as the "*ability to consolidate instances*." This ability helps explain the partial correlations in performance among learning domains and the comorbidity often observed in learning disorders.

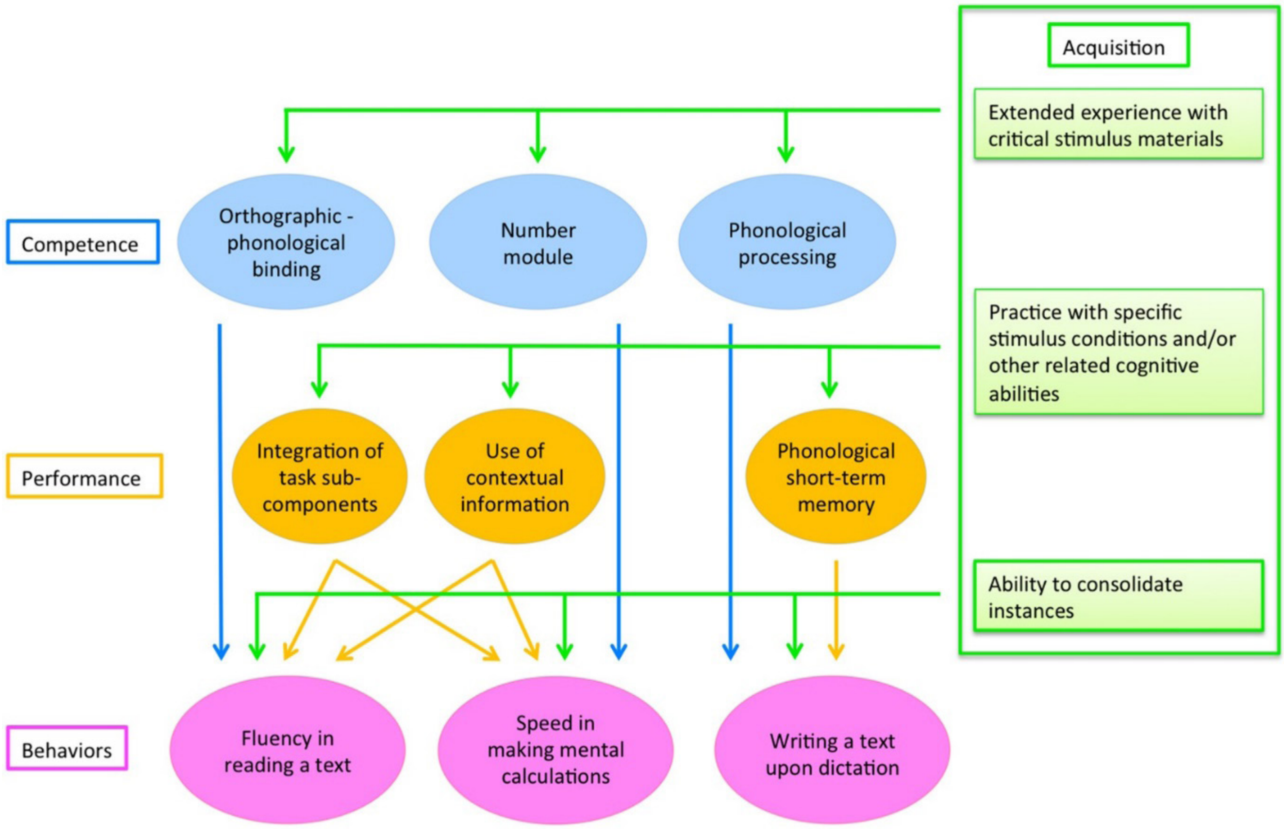

Figure 1. A multi-level model of learning cognitive skills (from Zoccolotti et al., 2020b).

Another relevant aspect of the model is that behavior is influenced not only by competence factors but also by "performance" factors. The distinction between competence and performance was first introduced by Chomsky (1966) in the context of language[1]. According to this distinction, what is measured behaviorally is not solely dependent on competence; it is also influenced by other factors, such as memory and attention. These influences

1 Note that similar (though not identical) distinctions have been put forward in the literature, such as resources versus performance (Shallice, 1988), representational versus processing (Bishop, 1997) or latent versus manifest variables (Toraldo, 2022).

go beyond the impact of competence factors alone. Notably, standard testing does not allow for the separation between competence and performance components. In both clinical and experimental settings, what is observed is a combined effect of competence and performance factors. Examples of performance factors include the ability to use contextual information and to integrate the sub-components of a task. One task that aims to measure this latter process is the Rapid Automatized Naming (RAN) task (Denckla & Rudel, 1976; for a review, see Kirby et al., 2010). In this task, children rapidly name a series of simple visual targets, such as color patches or digits. This ability is closely related to reading fluency and the quick execution of arithmetic operations (Koponen et al., 2017). However, RAN tasks do not predict accuracy in reading or math tasks (Koponen et al., 2017). In summary, the model recognizes that various performance factors can influence specific behaviors, contributing to the partial associations between different learning domains.

In our further research, we subjected this model to direct experimental testing. One study examined how children learn a new task over multiple repetitions (Marinelli et al., 2021). Consistent with previous findings, we observed that children improved their performance with each repetition, which was well described by a power function, as early suggested by Newell and Rosenbloom (1982). The individual parameters of this power function, particularly the scaling parameters, predicted performance in tasks that required knowledge of individual items across various learning domains. Examples include multiplication tables, spelling words with unpredictable transcriptions, and making orthographic decisions. In contrast, the power function parameters did not predict performance on tasks that involved applying rules or algorithms, such as judging numerosity or spelling through sublexical mapping (Marinelli et al., 2021). These findings support the idea that an individual's ability to consolidate instances is a skill that transcends different domains. This skill enhances performance when recalling individually learned items (or instances) and helps to efficiently complete a task (Zoccolotti et al., 2020b). In another study using the same learning paradigm on adult participants (Marinelli et al., 2025), we recently found lower performance at learning tasks only in young adult participants with a deficit in instance retrieval from memory, such as arithmetical fact retrieval and ambiguous word spelling or judgment. Subjects with a deficit in applying a serial algorithm (such as counting, calculation, or the sublexical application of mapping rules in reading and spelling) performed similarly to control participants in the learning task.

In a separate study, we investigated whether the predictions of our model could enhance the understanding of relationships among different learning domains when assessed with standard clinical tests (Zoccolotti et al., 2021). This study evaluated the performance of an unselected group of children in grades three to five on reading, spelling, and math tests. We utilized network analysis, a method well-suited for examining the relationship among various domains. The results showed that different measures of the same skill–reading, spelling, and math–formed distinct clusters, supporting that these abilities are based on distinct competencies. Consistent with our model's predictions, two central nodes in the network that connected the different learning domains were associated with tasks requiring knowledge of individual items: the arithmetic facts subtest and spelling words with ambiguous transcription. However, the study lacked a specific measure of lexical reading. Thus, one of the goals of the present research is to correct this problem. Due to the lack of irregular words in reading in Italian orthography, we assessed individual item knowledge with an orthographic judgment task. In this task, children must determine the correctness of the spelled word. We include correct words and phonologically plausible incorrect options, ensuring that accurately identifying the correct words requires referencing a specific lexical entry.

In this study, we aimed to confirm and extend the findings of Zoccolotti et al. (2021). To achieve this, we administered a series of reading, spelling, and math tasks to children attending primary school (for whom we expected limited differences in the association among these skills based on age/grade). We analyzed the data using network analysis. Based on the multi-level model of learning cognitive skill learning proposed by Zoccolotti et al. (2020b), we made several predictions. First, we anticipated that tests within each learning domain would be intercorrelated, supporting the presence of distinct competencies. Second, we expected that the critical nodes connecting different learning domains would be identified through tasks requiring knowledge of individual items or instances. Third, previous research has revealed that lexical influences in Italian emerge particularly by favoring reading fluency. Thus, we anticipated a strong link between reading fluency and orthographic judgment (but potentially with instance-based tasks in other learning modalities as well). Finally, we predicted that we would observe connections related to "performance" components associated with factors such as stimulus format or type of response.

Methods and materials

Participants

Ninety-eight primary school students (56 males, 42 females; mean age: 8.19 years, range: 7.06 - 11.03). The group is composed of 29 2nd graders (19 males, 10 females; mean age: 7.68 years, range: 7.06 – 9.16), 61 4th graders (32 males, 29 females; mean age: 9.62 years, range: 8.36 – 10.26) and 8 5th graders (5 males; 3 females; mean age: 10.59, range: 9.52 – 11.03). All participants were monolingual, had adequate performance (above 15° percentile scores) on the Raven CPM test (Pruneti et al., 1996) and had regular school attendance. The data were collected from public schools in areas around Foggia with a medium socioeconomic background; however, we did not collect individual data on socioeconomic status.

The study was conducted according to the principles of the Helsinki Declaration and was approved by the Ethic committee of Psychological Research of the Humanities Department of University of Foggia (N. 011/ CEpsi, 2/5/23). Parents gave their written consent to son's participation to the study.

Materials

Reading measures

We examined text reading speed and accuracy using the "*MT Reading test*" (Cornoldi & Colpo, 1998). The child reads a text passage aloud with a 4-minute time limit. Reading speed is measured in syllables per seconds. Reading accuracy is based on the number of errors. A score of 1 is given to each word with an elision (e.g., "casa" instead of "cassa" – in English "box"), substitution (e.g., "caspa" instead of "cassa"), insertion (e.g., "ciassa" instead of "cassa") or inversion of a letter (e.g., "csasa" instead of "cassa"), to omitted or inserted words, to pauses longer than 5 seconds and to skipped or repeated rows. A score of 0.5 is given to stress errors (e.g., "sabàto" instead of "sàbato" - in English Saturday), spontaneous self-corrections (e.g., the child says "sapato…sabato" for reading the word "sabato"), errors that do not change the meaning of the text (e.g., "anziano re" instead of "vecchio re" – in English "elderly king" for "old king"), and hesitations (e.g., the child says "sab…saba…sabato" or "cas…cassa" for reading "sabato" and "cassa", respectively). Self-corrections of 0.5 score errors are not penalized. If the participant makes two or more errors on the same word, the highest score is assigned. If the child makes several mistakes on the same word, he is penalized only once, attributing the most serious error. If the child does not complete the passage reading, the number of errors adjusted for the amount of text read is scored. The reported test-retest reliability coefficients range from 0.75 to 0.87 for accuracy and from 0.94 to 0.97 for speed, depending on grade level (Cornoldi & Colpo 1998).

The retrieval of orthographic representations (i.e., lexical reading) was assessed through an *Orthographic judgment* test. In this test, the child must silently read a list of irregular words (and corresponding derived pseudo-homophones) and judge their orthographic correctness. Pseudo-homophones were homophonic to the original words but orthographically incorrect for the presence of a phonological plausible error. Then, pseudo-homophones were detectable only through the retrieval of lexical representations. In this vein, the ability to deal with pseudo-homophones in the Orthographic judgment task represents a unique indicator of the efficiency of lexical reading in a fully transparent orthography in reading such as Italian.

Words could contain the following inconsistently spelled segments: (a) the phonemic group [kw] that is sometimes transcribed as CU and other times as QU–for example, CUOCO [ˈkwɔko], cook, versus QUOTA [ˈkwɔta], quote; (b) the syllables [t_e], [_e], [dʒe], which are written as CIE, SCIE, and GIE in some words and CE, SCE, and GE in others–for example, CIECO [ˈtʃɛko], blind, versus CECO [ˈtʃɛko], Czech; SCIENZA [ˈʃɛntsa], science, versus ADOLESCENZA [adoleʃˈʃɛntsa], adolescence; (c) words containing segments [nj]–[ɲ], which are homophonous to the extent that [opinjone/opiɲone], opinion, is spelled OPINIONE and not OPIGNONE, while [oɲuno/onjuno], everyone, may be spelled OGNUNO and not ONIUNO. Fakes derived from inconsistently spelled words were pseudo-homophones (i.e., they resulted in a string that is homophonous to the target, e.g., *SQUOLA* derived from SCUOLA, school and then detectable only by relying on the lexical procedure). The task includes regular words (i.e., not containing any inconsistent phonemic segment) and derived fakes (detectable through either the lexical or the sublexical procedure) as fillers. For more details, see Zoccolotti et al. (2020a, b) and Marinelli et al. (2017). The measure of performance was the percentage of wrong responses on the total amount of irregular stimuli. Given the dichotomous type of responses, we computed the reliability using the Kuder-Richardson 20 (KR-20) coefficient based on a large dataset (N = 244). The test indicated a high level of internal consistency at all grades (2nd grade: 0.89; 3rd grade: 0.90; 5th grade: 0.87).

Spelling measures

We used the "*Test for the Diagnosis of Orthographic Disorder, DDO-2*" (Angelelli et al., 2016): we used three of the four sections of the test. In particular, we did not administer section A of regular words because they do not allow us to evaluate whether they are spelled with the lexical or sublexical procedure. We have administered the following sections:

- Section B: Words requiring the application of context-sensitive sound-to-spelling rules (N = 15): These are regular transcription words requiring syllabic conversion (not 1-phoneme to 1-grapheme). Stimuli contain the phones [k], [g], [tʃ], [dʒ], for which the correct spelling of the consonant depends on the vowel that follows. For example, the phoneme [g] is written G when it is followed by the vowels A, O, and U (for example, "GATTO" [cat]) and GH when it is followed by E or I (for example, "GHISA" [cast iron]). The test-retest reliability coefficient for this section is available only for 5th grade ($r = 0.65$; $p < .0001$)
- Section C: irregular words with a potentially ambiguous transcription (N = 55): these are words with an unpredictable transcription along the phonological-to-orthographic conversion route requiring the retrieval of the orthographic representation of the word from the lexicon. In Italian, for example, the phonemic group [kw] can be written as QU, CU, or CQU, and all these orthographic alternatives were phonologically plausible and homophone; only the lexical procedure allows the correct spelling of stimuli such as these. (e.g., [kw] in ['kwɔta], i.e., quota is transcribed as QUOTA and not *CUOTA). The test-retest reliability coefficient for this section is available only for 5th grade ($r = 0.84$; $p < .0001$)

- Section D): pseudowords (N = 25): pseudowords with regular phoneme-grapheme mapping with one-sound-to-one-letter correspondence, helpful for assessing the sublexical procedure. The test-retest reliability coefficient for this section is available only for 5th grade (r = 0.55; p < .0001)

Words and pseudowords were given in separate blocks in a quasi-randomized order. The examiner read each item aloud in a neutral tone. The children had to repeat each item before writing it down (so that the examiner could be sure they understood the item). They were permitted to write in either capital or lower-case letters. No feedback was provided on the accuracy of the written response. The measure of performance was the number of stimuli correctly spelled in each section. Self-corrections were accepted. Test-retest reliability coefficients are reported only for 5th grade (section B = 0.65; section C = 0.84; section D = 0.55).

Math measures

We assessed calculation skills with the "*AC-MT arithmetic achievement test*" (Cornoldi et al., 2002). The child mentally performs three sums and three subtractions involving two-digit numbers as quickly and accurately as possible. Calculation accuracy is scored by summing the total number of correct responses within a 30-second time limit. An error is scored whenever the child does not respond within this timeframe. Calculation speed is measured by summing the seconds taken to complete each calculation (with a maximum of 30 seconds for each operation).

We assessed whether children stored arithmetic facts and could retrieve the results of basic operations or multiplication tables automatically from memory through the Arithmetic Facts Test (Cornoldi et al., 2002). Children are required to recall arithmetic facts, each within a 5-second time limit. Responses given beyond this time limit are considered incorrect. The measure of performance is the total number of correct responses.

The authors of this test (Cornoldi et al., 2002) provide test-retest reliability values only for global indices, which include the measures used in this study. The reported test-retest reliability coefficients range from 0.77 to 0.35 for the accuracy index and 0.63 to 0.62 for the speed index, depending on grade level.

Data Analysis

We converted performance on each subtest to z-scores based on the means and standard deviations of the 2nd, 4th, or 5th-grade samples. We used algebraic signs so that, in all cases, positive values indicated better performance and negative values lower performance. Specifically, for tasks where performance is measured by an error score (as described in the materials section), the resulting z-score was multiplied by -1.

Data were submitted to network analysis, a method to explore the relationships between variables. A network consists of a set of nodes representing the variables of interest connected by edges indicating the relationships between these variables. To estimate the edges, we used the Gaussian Graphical Model (GGM), in which the edges represent regularized partial correlation coefficients between two variables after controlling for all other variables in the network (Epskamp et al., 2018). The estimation of partial correlations can produce rich inferences as variables that directly activate each other will be connected, assuming all relevant variables are included in the model (Wysocki & Rhemtulla, 2021). To this end, a relevant aspect of GGMs is the ability to identify not only partial correlations but also truly zero edges, thereby achieving a sparse network. Setting edges to zero is a key feature of network estimation as, from a theoretical standpoint, having a fully connected model is less helpful than having a few potentially meaningful connections. The sparsity induction is achieved using a penalty parameter λ, which may be calculated using various methods. The selection of the penalty parameter λ is critical as different values applied to the same data can result in different networks (Epskamp & Fried, 2018). For example, when $\lambda = 0$, the network is no longer penalized, and, assuming no sample partial correlations are precisely zero, the resulting network is fully connected (i.e., all edges are non-zero). As λ increases, so does the penalization of the network, resulting in an increasingly sparse network (i.e., fewer edges are estimated), eventually resulting in an empty network (Liu, 2013). In this study, the Rotation Information Criteria (RIC) was used to determine λ. The RIC randomly rotates the rows within each column, creating a rotated dataset with only spurious relations between its variables. The RIC then finds the smallest value of λ that will accurately regularize all (spurious) edges to 0. This method was chosen because it appears to be less influenced by the sample size compared to other alternative approaches and tends to strike an optimal balance between sensitivity and false positive rate (Wysocki & Rhemtulla, 2021).

The stability of the resulting network was estimated by a non-parametric bootstrapping procedure, which recurrently estimates the model under resampled data (Epskamp et al., 2018). The data were resampled 1000 times, obtaining an average edge value and a 95% confidence interval (CI) for each edge. The CI of each edge provides relevant information about the replicability of the resulting network. The edges that do not include 0 in their CI are more likely to be replicated; when the CI touches 0, the edge has some chance of not being found in a different data collection, and edges that cross 0 are unreliable because they may have an opposite sign in a different sample (Zoccolotti et al. 2021; Epskamp et al., 2018).

We also calculated three different centrality indices (*strength*, *betweenness* and *closeness*) to investigate the importance of each node in the network's structure. Centrality indices can be seen as operationalizations of a node's importance based on the pattern of the connections in which the node of interest plays a role (Epskamp et al., 2017; Costantini et al., 2015). *Strength* centrality is defined as the sum of the absolute weights of the connections, incident to the node of interest, and quantifies how well a node is directly connected to other nodes. *Betweenness* and *closeness* centrality indices are related to the concept of the shortest path, i.e., the minimum number of steps to get from one node to another. *Betweenness* centrality is defined as the number of shortest paths that pass through the node of interest, and it quantifies how important a node is in the average path between two other nodes. *Closeness* centrality is defined as the average length of the shortest path between the node and all other nodes in the network, and it quantifies how well a node is indirectly connected to other nodes.

The analyses were performed using JASP (van Doorn et al., 2021). JASP (Version 0.16.4) is software that bases the network modules on the bootnet (Epskamp et al., 2018) and qgraph (Epskamp et al., 2012) packages of the R statistical software (R Core Team, 2017).

Results

We performed a network analysis to explore the relationships between reading, spelling, and math skills. Figure 2 represents the best network estimated from the data, representing the relationships among the variables examined.

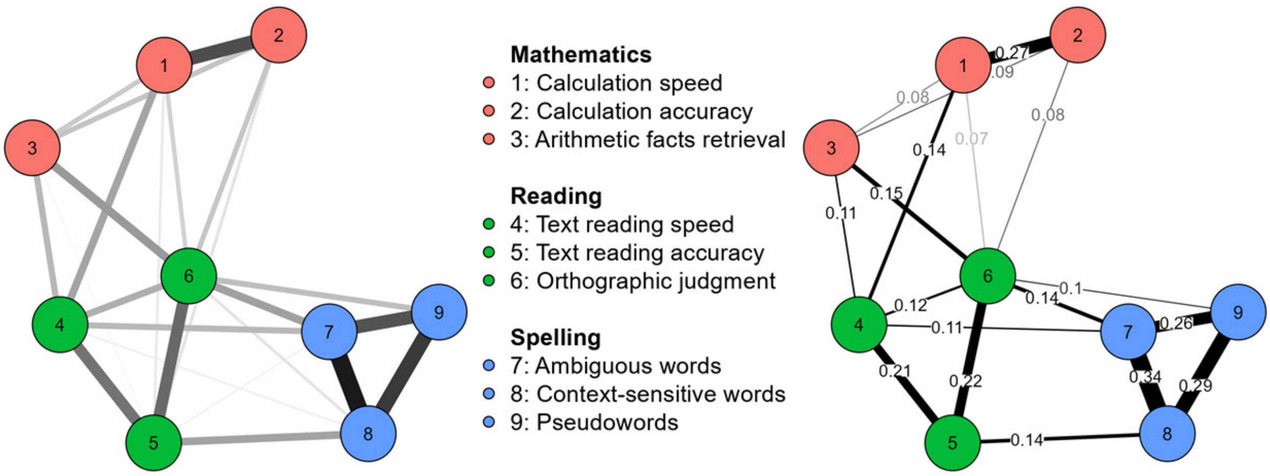

Figure 2. The left panel reports every edge estimated as different from 0 by the Gaussian Graphical Graphical Model, adopting the Rotation Information Criteria (RIC) method. The edges represent regularized partial correlations. The right panel shows the same network with graphical changes to improve the readability of the most important connections. Specifically, only edges > 0.06 are shown.

Table 1 presents the exact values of all edges and the simple correlations among all variables. The simple correlations (above the diagonal) were transformed into regularized partial correlations (network weights presented below the diagonal). In some cases, an association in the simple correlation became a zero edge after the regularization, indicating that the association was spurious, i.e., entirely due to the influence of other factors.

Table 1. Simple and regularized partial correlations among variables. The simple correlations (Pearson's r) appear above the diagonal. Network weights correspond to the regularized partial correlations and appear below the diagonal.

Variable	Mathematics			Reading			Spelling		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(1) Calculation speed		.59	.43	.44	.48	.53	.26	.24	.21
(2) Calculation accuracy	.27		.45	.29	.45	.46	.26	.24	.19
(3) Arithmetic facts	.08	.09		.44	.43	.40	.21	.28	.21
(4) Text reading speed	.14	0	.11		.66	.55	.48	.46	.35
(5) Text reading accuracy	.03	.04	.01	.21		.63	.45	.57	.43
(6) Orthographic judgment	.07	.09	.15	.12	.23		.54	.58	.52
(7) Ambiguous words	0	0	0	.11	.01	.14		.77	.75
(8) Context-sensitive words	0	0	0	.02	.14	.04	.35		.73
(9) Pseudowords	0	0	0	0	0	.10	.26	.30	

Table 2 presents the Centrality measures (Strength, Betweenness, and Closeness) per variable; Figure 3 reports the bootstrap results.

Table 2. Centrality measures per variable.

Variable	Strength	Betweenness	Closeness
(1) Calculation speed	.590	4	.009
(2) Calculation accuracy	.490	0	.009
(3) Arithmetic facts retrieval	.440	0	.010
(4) Text reading speed	.710	10	.013
(5) Text reading accuracy	.780	4	.013
(6) Orthographic judgment	.930	14	.014
(7) Ambiguous words	.870	10	.012
(8) Context-sensitive words	.840	4	.011
(9) Pseudowords	.660	0	.010

Several key observations originate from an analysis of Figures 2 and 3 and Tables 1 and 2 based on our general expectations.

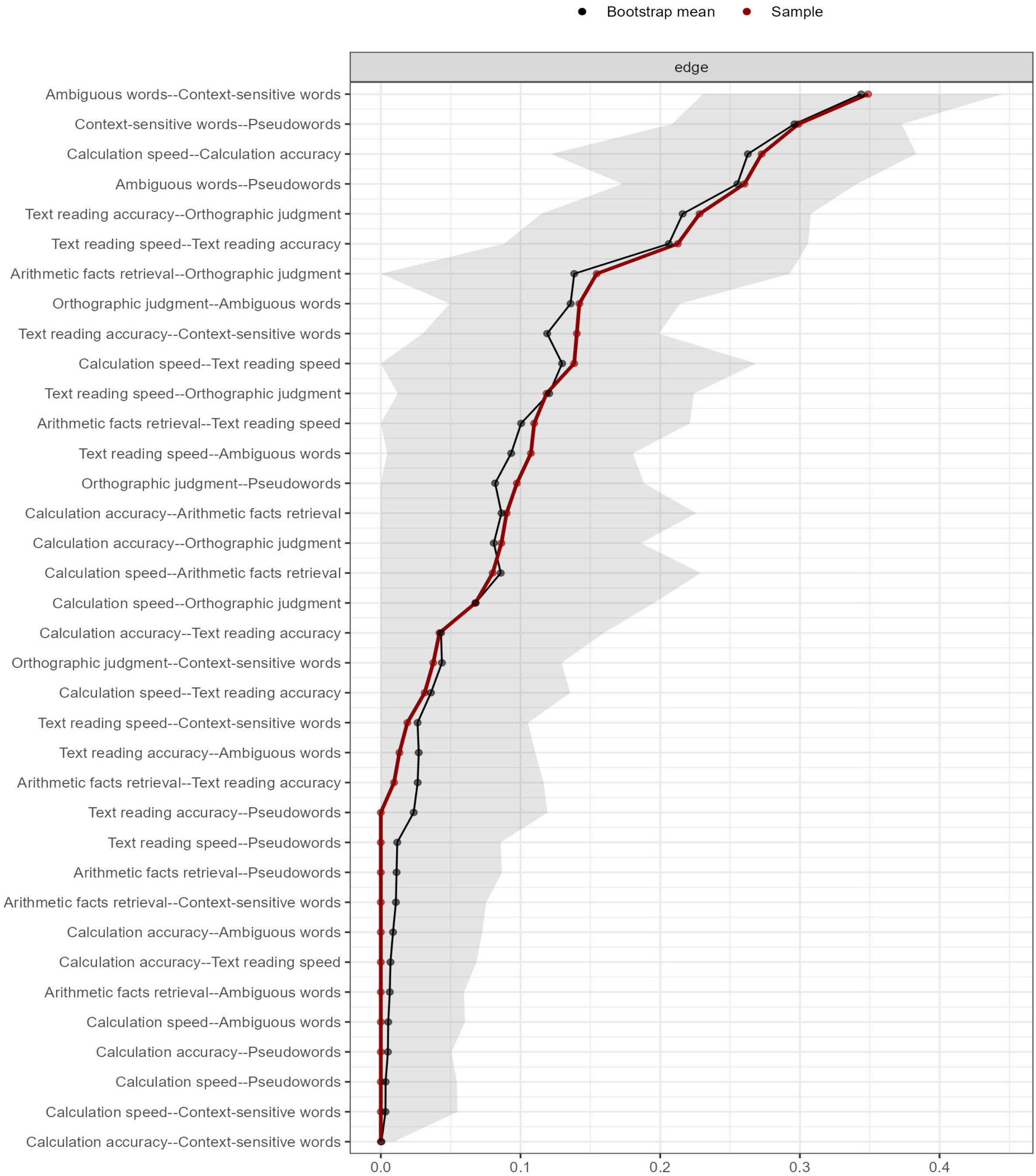

Figure 3. Full list of edges and results from the 1000 bootstraps. Red dots indicate the edge value the estimated network. Black dots indicate the average edge value over 1000 bootstrap resampling. The grey shadow represents the 95% confidence interval estimated with the bootstrap resampling. Edges are ordered by their estimated strength.

A first expectation was that tasks would be inter-correlated within each learning domain. Results are consistent with this expectation. There were positive links within reading, as well as spelling and math tests.

A second expectation was that the association among different learning domains would be largely mediated by tests mapping the retrieval of individual memories (instances). Several results are consistent with this expectation:

- The strongest link between reading and math (.15) is that between Orthographic judgment (6 in the Figure) and Arithmetic facts retrieval (3), i.e., two tests resting on the retrieval of individual memories (instances).
- Similarly, a strong link between reading and spelling (.14) is that between Orthographic judgment (6) and Ambiguous words (i.e., Spelling of words with ambiguous transcription, 7), again two tasks which emphasize the retrieval of individual memories.
- Bootstrapped confidence intervals of the two aforementioned edges (Arithmetic facts retrieval – Orthographic judgment; Orthographic judgment – Ambiguous words) do not contain 0. Thus, they are likely to be replicated in other samples.
- Contrary to our expectation, there was no link between Ambiguous words (7) and Arithmetic facts retrieval (3).
- Orthographic judgment and Ambiguous words (but not Arithmetic facts retrieval) emerged as the nodes with higher strength centrality, i.e., they have the most direct influence in the network.
- Orthographic judgment and Ambiguous words (but not Arithmetic facts retrieval) emerged as the nodes with higher betweenness centrality, i.e., they are particularly relevant to connect other nodes in the network. In this vein, it is of note that Orthographic judgment, the task with the highest betweenness value, showed significant links with tasks outside the reading domain (*i.e.*, Pseudowords, .10; Calculation speed, .07; and Calculation accuracy, .08).
- Orthographic judgment, Ambiguous words, and Arithmetic facts retrieval emerged as the nodes with higher closeness centrality of their specific domain (reading, spelling, and mathematics, respectively). Thus, they have a higher indirect influence on nodes of other domains.

A third expectation was that lexical retrieval allows faster reading time. Consistently, reading speed was associated not only with the Orthographic judgment task (.12) but also with tasks based on instance learning in other learning domains, i.e., Spelling of Ambiguous words (.11) and Arithmetic facts (.11).

A final expectation was that further associations among different learning domains would be due to specific (performance) factors. Some associations appear interpretable along these lines:

- There was a substantial link (.13) between Reading speed (1) and Calculation speed (7). Note that this link seems closely associated with a speed component. Thus, there was no link between Reading speed (1) and Calculation accuracy (8) and only a weak link (.03) between Calculation speed (7) and Reading accuracy (2).
- Another strong connection (.14) was present between Reading accuracy (2) and Context-sensitive words (see comments in the Discussion section). Notably, these two tests did not present other strong connections other than those within their learning domain.

Discussion

The network analysis partly supported the predictions based on the multi-level model of learning cognitive skills (Zoccolotti et al., 2020b). A key aspect of the model is that it aims to identify both the factors contributing to the distinctness of different learning domains and those contributing to explaining their partial overlap. The network analysis evidenced positive links within each area, consistent with the idea that reading, spelling and math refer to three partially distinct domains calling for different core competences. This finding confirms previous similar observations by Zoccolotti et al. (2021).

However, there were also several cross-domain links. The model predicts that a key factor accounting for the overlap among different learning domains refers to a dimension referred to as the "*ability to consolidate instances*", i.e., the capacity to acquire and retrieve individual memories. In standard clinical tests, such as the ones examined here, this dimension refers to tasks which, to be solved, require the reference to individual memories, such as correctly spelling a word with ambiguous transcription or quickly retrieving the solution of an arithmetic operation. The network analysis was broadly consistent with the predictions that the three tests measuring instance-based processing were critical in linking the three learning domains. Thus, Orthographic judgment and Arithmetic facts retrieval were closely related, as was the case for Orthographic judgment and Ambiguous words. Therefore, also these results broadly confirm previous observations by Zoccolotti et al. (2021) and extend them to a task on reading (Orthographic judgment), which was not present in our former study.

The effectiveness of the three markers of instance processing in linking different learning areas was somewhat different. Thus, the Orthographic judgment task was the most prominent test, as indicated by centrality measures of strength, closeness and betweenness. This latter parameter indicates that Orthographic judgment was the task mediating several relationships among different tests, also having the most robust direct and indirect influence on other measures. The strength and mediation capacity of the other two instance retrieval markers were lower, and the two tasks (Ambiguous words and Arithmetic facts retrieval) were not significantly associated. This pattern was unanticipated, and further experimental work seems needed to understand this discrepancy. One can speculate that other factors may contribute to mediating these differences. For example, diverse clinical tests may best capture individual differences in instance-based processing at different ages. We examined children spanning from 2nd to 5th grade. However, the sample was too small to carry out separate networks as a function of age/school experience. Further work on larger samples seems required for this goal. Despite these qualifications, a promising indication comes from results on the closeness centrality index, which provides a measure of the indirect influence of a measure on others in the network. As previously stated, in our study, one task was considered an indicator of retrieving single instances from memory in each learning domain. These specific tasks showed the highest closeness centrality values among the other measures within their domain, influencing the network more than other domain-specific measures.

Notably, there are different hypotheses concerning the association of learning processes/disorders. One well-known theoretical account is the procedural deficit hypothesis (PDH) (Ullman, 2004; Ullman et al., 2020; Nicolson & Fawcett, 2007), which was developed prevalently in terms of the comorbidity of learning disorders. Accordingly, a deficit in procedural (as opposed to declarative) learning underlies dyslexia and other developmental disorders as well as their comorbidity. Research on the PDH has been extensive but with quite variable results. Thus, the various reviews which have critically examined this literature (Lee et al., 2022; Lum et al., 2013; Schmalz et al., 2017; van Witteloostuijn et al., 2017; West et al., 2021) have reached quite different conclusions. The present results appear inconsistent with the PDH. If one were to predict that the association among different learning domains is mediated by procedural processing, one would expect that tasks mapping onto the application of rules (such as the spelling of pseudo-words) would play a central role in the network. In contrast, as stated above, this role was taken most clearly by tests that place a critical role on item-based processing, such as Orthographic judgment. In a theoretical paper, we have proposed that a direct contrast between rule-based versus item-based processing is crucial to understanding which factors contribute most clearly to the association among learning processes and conversely to the genesis of comorbid learning disorders (Marinelli et al., 2024). We have recently provided confirmatory experimental evidence for this hypothesis in a study on adults with learning disorders (Marinelli et al., 2025).

Of note are also the widespread associations of reading speed, which was associated with every task requiring instance retrieval (such as arithmetical facts, spelling of ambiguous words and orthographic judgement). In Italian, the orthography object of the present study, the high consistency allows a near-perfect reading accuracy rate even in the absence of lexical retrieval. The strongest indicators of lexical deficiency in Italian are reading slowness and sounding out behavior, both indicative of fractionated text decoding (Marinelli et al., 2023; Zoccolotti et al., 2018). In this framework, reading speed might be considered an indicator of lexical retrieval. For this reason, it is unsurprising that reading speed was associated with lexical retrieval in spelling and judging (i.e., reading) ambiguous words. The association of reading speed with the Arithmetical fact test further supports the hypothesis that the association between reading, spelling and math skills is due to efficiency in instance retrieval. This finding is consistent with Zoccolotti et al. (2021) results and extends to the Orthographic judgment task, a task of lexical reading not included in Zoccolotti et al.'s (2021) study. The simultaneous examination of reading speed and orthographic judgment in the same model might have made the association between lexical efficiency (in both reading and spelling) and arithmetic facts retrieval less evident. The network analysis estimated the independent association of any skill with other abilities, net of the covariance shared with other variables in the network.

One further set of predictions of the multi-level model of cognitive skill learning (Zoccolotti et al., 2020b) is that some associations among different learning areas may be mediated by format or response characteristics, *i.e.*, "performance" factors. We identified two such cases in the observed network. First, we noted a strong link between Reading speed and Calculation speed. This connection appears closely associated with the speed requirement. There was no association between Reading speed and Calculation accuracy and between Calculation speed and Reading accuracy. This finding presents some similarities to observations on RAN tasks. We know that RAN predicts reading and calculation speed but not reading and calculation accuracy (Koponen et al., 2017). Another strong link was between Reading accuracy and Context-sensitive words. Spelling context-sensitive words requires a careful orthographic analysis to apply the complex rules that govern the not 1:1 orthographic mapping of letter clusters. Note that Italian has a set of complex context rules that apply in all cases (i.e., without exceptions). It appears conceivable that the close orthographic analysis required to implement the context-sensitive rules may be instrumental in obtaining an optimal level of reading accuracy. Identifying the performance factors which selectively contribute to the association among learning processes (and disorders) is particularly relevant. We know that reading (spelling and math) measures are always jointly influenced by competence and performance factors. Indeed, isolating the competence component is a complex task, although the interpretation typically tends to focus on competence factors and often dismisses the role of performance components. In Bishop's (1997) words: *"traditional cognitive neuropsychology places a disproportionate emphasis on representational (competence) deficits, with processing (performance) deficits being relatively neglected.*"

The results of this study offer a comprehensive overview of the relationships among various learning skills. In the introduction, we noted that previous studies on reading, spelling, and math have typically treated these areas as separate domains. As a result, despite the substantial evidence available, our understanding of how these skills are interconnected remains limited. Additionally, much of the existing research has focused on children with learning deficits, overlooking the entire population of children. There is an established tradition of studies examining the factors contributing to the partial overlap between developmental dyslexia and dysgraphia (e.g., Moll & Landerl, 2009; Angelelli et al., 2010). More recent research has begun to investigate the overlap between dyslexia and dyscalculia (e.g., Peters et al., 2020). However, the recent transdiagnostic approach has emphasized that a deeper understanding may emerge from methodologies designed to detect trends in the data without preconceiving specific diagnostic labels (Astle et al., 2022). The present research aligns with that theoretical perspective.

Limitations

Our study presents some limitations. First, we did not examine sublexical reading (with tasks such as pseudoword reading). So, we do not know whether this ability was associated only with lexical reading and sublexical spelling or other spelling and math skills. Moreover, we were interested in highlighting associations across learning domains, not developing models to explore skills contributing to each distinct core domain (i.e., reading, spelling and math). Network analysis is an exploratory technique that does not allow us to add too many predictors for this purpose. Thus, further studies using other types of analysis will be needed. Moreover, we did not examine associations in a clinical sample: it is possible that these findings may not be directly generalizable to populations with learning disabilities. An even more relevant test of Zoccolotti's (2020b) model would be to prove that cases with dissociated disorders do not have a domain-general deficit in the ability to acquire instances. Finally, various significant links were not explicitly anticipated based on the model. All these links involved a task with high betweenness values (Orthographic judgment). Further work is needed for a definite characterization of these relationships.

Conclusion

In conclusion, the study empirically supports the predictions of the multi-level model of cognitive skill learning proposed by Zoccolotti et al. (2020b). Reading, spelling, and math skills seem associated with a domain-general ability to acquire and retrieve instances from memory. These results are consistent with previous findings exploring the association across learning domains (Zoccolotti et al., 2021) and the relationship between learning skills and instance acquisition ability (Marinelli et al., 2021; 2025). This skill is involved in resolving arithmetical facts, spelling, and judging the correctness of irregular words that require lexical processing, as well as in fast and fluent reading.

This study highlights the importance of a transdiagnostic and multifactorial approach, which can detect factors contributing to the association and dissociation of learning disorders. Overall, our findings highlight the importance of jointly investigating all learning skills due to their high association, as well as domain-general factors that could explain their co-variation. Understanding the nature of the associations among learning domains may have relevant heuristic implications for our understanding of the locus of the comorbidity of learning deficits. This study has clinical and theoretical implications, allowing optimization of reading, spelling, and math learning models as well as diagnostic instruments. This study highlights the importance of exploring the ability of instance acquisition through tests which may capture an instance learning difficulty not bounded to a given modality (i.e., mathematical or orthographic materials; Marinelli et al., 2021; 2025). Thus, it is relevant to develop diagnostic instruments for this purpose. Finally, this study also highlights the importance of having diagnostic instruments capable of isolating each competence from performance components.

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